Benefits and Risks: Their Assessment in Relation to Human Needs*

by T.A. Kletz

Safety officers, managers, and designers face a constant dilemma. Some accidents are unlikely to kill or injure anyone if they do occur. Nevertheless, they might happen, and so they feel they must do something about them lest they be partly responsible for someone's death or injury. But to remove every possible risk, however slight, is impossible. How do we decide which risks should be dealt with first, and which can be left, at least for the time being? In short, how do we allocate our resources?

In the past the dilemma of balancing risk against cost was often resolved by spending lavishly to remove all possible risk from hazards that had been brought to light by an accident and ignoring the rest It was sometimes necessary to avoid looking too hard for other hazards in case more were found than could be dealt with. Such a method is, of course, wrong. Whether resources are large or small we should spend them in a way which maximises the benefit to our fellow men and can be logically defended. The latter point is important. If I say that the risk from lightning, the transport of chemicals, or rock climbing is small and should be ignored, while you say it is high and demands immediate attention, discussion between us is difficult. If, however, there is an agreed scale for measuring risk, a dialogue becomes possible.

We should bear in mind that we are all at risk all the time, whatever we do, even if we stay at home. We accept risks when we consider that by doing so something worthwhile is achieved. We go rock-climbing or sailing or smoke because we consider the pleasure worth the risk. We take jobs as airline pilots or soldiers, or become missionaries among cannibals, because we consider the pay, or the interest of the job, or the benefit it brings others, makes the risk worthwhile. In industry, whatever we do to remove known risks, there is likely to be some risk, however slight, to employees and to local members of the public. By accepting the risk we earn our living and we make goods that enable ourselves and others to lead a fuller life.

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Different numerical approaches

Attempts have been made, particularly during the last ten or fifteen years, to use numerical methods for setting priorities in safety matters These attempts, known as 'hazard analysis', have used two distinct methods.

Weighing in the balance. In this method, sometimes known as the trade-off, the benefits and disadvantages of various courses of action are expressed in common units, usually money, so that they can be offset against each other and the course of action giving the biggest net benefit identified. We weigh in the balance the pros and cons of each proposal. For example, we can compare the cost of preventing an accident with the costs of the damage and injury it will produce, multiplied by the probability that it will occur. We can compare the cost of preventing pollution with the cost of damage caused by it.

In the United Kingdom this approach is sanctified by law. The words 'reasonably practicable', which occur so often in British safety legislation, have been defined as implying 'that a computation must be made in which the quantum of risk is placed on one scale and the sacrifice involved in the measures necessary for averting the risk (whether in money, time or trouble) is placed in the other, and that, if it be shown that there is a gross disproportion between them – the risk being insignificant in relation to the sacrifice – the defendants discharge the onus on them' Ref. [1].

Weighing in the balance is satisfactory if we are considering accidents that could cause damage to plant and loss of production, but are unlikely to injure anyone. However, when we consider accidents that may kill or injure people, it becomes more difficult, despite what the law says, because we have to put a value on human life Many courageous attempts have been made to do so Refs. [2, 3], but they have not been universally accepted and it is desirable to avoid using these figures if we can.

Indirect consequences of accident are similarly difficult to evaluate. Thus attempts to put money values on the intangible effects of pollution have proved difficult. Overall balances have been achieved in only a few cases Refs. [4, 5] and the results have not been widely accepted.

For these reasons, most of the attempts to apply numerical methods to safety problems have used the second method, standard or target setting. This is the method used by the law in the United Kingdom, in practice if not in principle.

Standard or target setting. A company, industry, or government sets a standard which must be achieved, or a target which should be aimed for. Such standards or targets cover widely diverse hazards. For exemple, they specify the height of handrails; the concentrations of toxic chemicals in the atmosphere; the level of noise in places of work; or the amount of pollutants that may be discharged to the atmosphere or a river. Ideally, such targets should be so set that the levels of risk are comparable; we should not spend money on raising the height of handrails if the risk of falling over them is smaller than the risk of being harmed by toxic chemicals in the atmosphere. In practice, of course, the targets used are often out-of-line, even within the same industry.

I shall now describe some methods that have been developed, using this second approach, to help us allocate our resources rationally in safety matters. They have been developed mainly to deal with problems arising from acute, or immediate, hazards such as fires, explosions, and large releases of toxic gas, but attempts are now being made to apply them

Table 1. FAFR Values for Various UK Industries

Clothing and footwear	0.15
Vehicles	1.3
Chemical industry	4
British industry (i.e., all premises covered by the Factories Acts)	4
Metal manufacture and shipbuilding	8
Agriculture	10
Coal mining	14
Fishing	36
Railway shunters	45
Construction erectors	67

to chronic, or long-term, hazards. The justification of these methods is not, of course, that they are philosophically sound, though one would like to think that they are, but that they help people in industry to use their resources more effectively to the greater benefit of their fellow men. They are essentially designed for use by practical people. Further details are given in references [6-12].

Risks to employees

Before we can set a target for safety, we need a scale for measuring it. A scale that has been found convenient is the fatal accident frequency rate (FAFR); that is, the number of fatal accidents in a group of 1000 men in a working lifetime (100 million hours). The British chemical industry's FAFR is about 4 exluding the disaster at Flixborough, or about 5 if Flixborough is averaged over a 10 year period. Figures for some other industries are shown in Table 1.

About half the chemical industry's FAFR is made up of risks unconnected with the nature of the industry, such as falling downstairs or getting run over by a vehicle. The balance is made up of special chemical risks, such as fire, explosion, and toxicity. If we are sure in the chemical industry that we have identified all the special risks attached to a particular job, we set as our specification that the man doing the job should not be exposed to FAFR, for these special risks, greater than two. As a matter of priority, such risks will be eliminated or brought within this limit on new or existing plants.

On most plants, we cannot be sure that we have identified all the special risks, so we specify that any single one, considered in isolation, should not expose an employee to an FAFR greater than 0.4. We will eliminate or reduce, as a matter of priority, any such hazard on a new or existing plant that exceeds this figure. We are thus assuming that on a typical plant there are about five special risks.

If a job is manned by one man for 2000 hours per year an FAFR of 0.4 is equivalent to one fatality every 125 000 years. If the job is manned continuously on shifts, then it is equivalent to one fatality every 30 000 years.

Experience has shown that the costs of doing this, though often substantial, are not unbearable They involve the chemical industry in expenditure which some of our competitors do not incur Some of this can be recouped in lower insurance premiums, some by the greater plant reliability that safety measures often produce; the rest is a self-imposed 'tax' which has to be balanced by greater efficiency.

Risks to the public

When we consider risks to the public at large from industry, the level of risk which can be considered tolerable, even in the short term, should be much lower. A man chooses to work for a particular employer or in a particular industry, and, unless he chooses a particularly hazardous occupation, the risks he runs are not much greater than if he stayed at home. On the other hand, the public may have risks imposed on them without their permission, and though society as a whole may gain, they may not. For example, not all people who live near airports wish to travel by air.

Chauncy Starr Refs. [13, 14] has pointed out that we accept voluntarily risks such as driving, flying and smoking, which expose us to a risk of death of one in 100 000 or more (sometimes a lot more) per person per year (a FAFR of 0.1). We also accept, with little or no complaint, a number of involuntary risks which expose us to a risk of death of about one in 10 million or less per person per year (a FAFR of 0.001). Table 2 lists a number of these voluntary and involuntary risks It must be stressed that the figures are only approximate and may have been calculated using different assumptions. Furthermore, some of the comparatively small number ot workers in this field copy from each other, so any error, once introduced, is repeated in various papers and acquires an aura of authenticity. Any individual figure should therefore be checked in the original sources if it is to be used in a calculation.

We accept very high risks voluntarily; we accept other risks, imposed on us without our leave, if they are sufficiently small. It would be possible to reduce the involuntary risks listed in Table 2 if there was sufficient pressure from the press and public, but on the whole there is no such pressure. The risk of being struck by lightning or falling aircraft is so small that we accept the occasional death without complaint. To quote the *Daily Telegraph* Ref. [18] commenting on calls for a crash programme of snowploughs in the United Kingdom: 'This is rather like insuring oneself against snake-bite or being struck by lightning. It is impossible to take precautions against everything'. We accept very high risks travelling in road vehicles, presumably because their advantages are clear and obvious. From natural disasters we accept risks of about one in a million per person per year; from man-made events, except road transport, we seem to accept about one in 10 million per person per year.

Leukaemia and influenza have been included in the list as examples of risks we do not readily accept; there is pressure for something to be done. Most people would support

Table 2. Voluntary and Involuntary Risks Compared

Voluntary		Involuntary	
Activity	Risk of death per person per year ($\times 10^{-5}$)	Activity	Risk of death per person per year ($\times 10^{-7}$)
Smoking (20 cigarettes/day)	500	Run over by road vehicle (USA)	500
Drinking (1 bottle wine/day)	75	Run over by road vehicle (UK)	450
Football	4	Floods (USA)	22
Car racing	120	Earthquake (California)	17
Rock-climbing	4	Tornadoes (Mid-West USA)	22
Car driving	17	Storms (USA)	8
Motor-cycling	200	Lightning (UK)	1
Taking contraceptive pills	2	Falling aircraft (USA)	1
Taking saccharin (average US consumption)	0.2	Falling aircraft (UK)	0.2
Eating peanut butter (4 tablespoonsful/day)	4	Explosion of pressure vessel (USA)	0.5
Diagnostic X-rays (average US exposure)	1	Release from atomic power station –	
Being in same room as smoker (average US exposure)	1	(at site boundary) (USA)	1
		(at 1 km) (UK)	1
		Fooding of dykes (Holland)	1
		Bites and stings of venemous creatures (UK)	1
		Transport of petrol and chemicals (USA)	0.5
		Transport of petrol and chemicals (UK)	0.2
		Leukaemia	800
		Influenza	2000
		Meteorite	0.0006
		Cosmic rays from explosion of supernovae	0.1–0.0001

Data mainly from Gibson Ref.[12], Starr Refs [13, 14], Pochin Refs.[15, 16] and Hutt Ref.[17] The last four figures on the left-hand side are estimated by Hutt assuming a linear response, and could be wrong if there is a threshold exposure below which no harmful effects occur.

action to reduce incidence of these diseases, but many would regard the others as hardly worth bothering about.

We thus have a basis for assessing risks to the public at large as a result of an industrial activity. If the average risk to those exposed is less than one in 10 million per person per year, it should be accepted, at least in the short term, and resources should not be allocated to its reduction. A risk of one in 10 million per person per year is, of course, extremely low. It may be easier to grasp if it is expressed as follows: Suppose all sources of death were removed except that resulting from a particular industrial activity, then all the people living near the factories concerned would live, on average, for 10 million years

The risk is a good deal lower than that proposed in the Canvey Island Report Ref. [19], a recent official report on the risks to the public from the oil refineries and similar industries on an island in the Thames estuary. However, the report, in many people's view, has exaggerated the size of the risks, and so the difference is not as great as it seems at first sight. The report itself admits on the last page that it may have exaggerated the risks, as it stated: 'Practical people dealing with industrial hazards tend to 'feel in their bones' that something is wrong with risk estimates as developed in the body of the report'. Nevertheless, the Report is a landmark in that it shows official acceptance of the view that we cannot do everything possible to avoid every conceivable accident, and that numerical methods should be used to decide what level of risk to accept.

The term 'acceptable risk' is one which many people find repugnant, and I can sympathise with their view. 'We should never', they say, 'deliberately accept risks to other people'. Of course, we should not, but we cannot do everything at once; some things have to be done first, others left until later Hazard analysis, to repeat what has been said earlier, is concerned with priorities rather than principles

Examples of hazard analysis

I would now like to give some examples of problems to which numerical methods and the criteria described in this paper or similar criteria have been applied in order to decide whether or not action should be taken to reduce the level of risk, or protect people from the possible consequences

A common industrial process is oxidation, in which air or oxygen is used to convert one compound into another. If too much air or oxygen is added there may be an explosion. Oxygen analysers are used to measure the oxygen concentration in the plant and if it approaches a dangerous level the supply of air or oxygen is usually cut off automatically. Nevertheless, a number of explosions have occured Ref. [20]. Such explosions pose a number of questions. How many oxygen analysers do we need to prevent explosions? Should we duplicate the shutdown system? Should we measure temperature and pressure as well as oxygen concentration and use them to isolate the oxygen supply? How often should we test these instruments? Hazard analysis can be used to answer these questions Ref. [21]

Note that complete elimination of the hazard is not an available option. We can reduce the probability of an explosion to any desired level by installing more and more instruments, at increasing cost, but complete safety is approached asymptotically. Unless, therefore we use hazard analysis we have no rational basis for deciding how much protective instrumentation to install.

Belts and braces

The argument of the preceding section can be illustrated by considering an everyday example based on the use of belts and braces. The accident we wish to prevent is the embarrassment of our trousers falling down through failure of the means of support. Let us assume that breakage through wear and tear is prevented by regular inspection and replacement, and that we are concerned only with failure due to faults in manufacture which cannot be delected beforehand and which are random events.

Let us assume further that, on average, each pair of braces breaks after 10 years' service, and that belts fail in the same way and as frequently as braces. Collapse of our trousers once in 10 years is not considered an acceptable risk.

How often will a belt and braces fail altogether? If one fails then this will not be detected until it is removed at the end of the day. Assuming it is worn for 16 hours per day, then on average every man is wearing a broken belt for 8 hours every 10 years and broken braces for 8 hours every 10 years.

The fractional dead time (FDT) of the braces is thus:

$$\frac{8}{16} \times \frac{1}{10} \times \frac{1}{365} = 0.000137$$

and the FDT of the belt is the same.

The chance of the second protective device failing while the first one is 'dead' is given by:

$$\text{Hazard rate} = \text{Demand rate} \times \text{FDT} = 2 \times \frac{1}{10} \times 0.000137 = 2.74 \times 10^{-5} \text{ per year,}$$

or once in 36 500 years.

Failure of belt and braces together, therefore, will occur once in 36 500 years. At the individual level this risk is acceptable. However, there are about 25 million men in Great Britain so that, even if every man wears belt and braces, 685 men will lose their trousers every year. At the national level it is considered unacceptable that so many men should be embarrassed in this way.

To reduce the risk further, every man could wear a third protective device, namely a second pair of braces. Simple calculation shows that this would reduce the failure rate for the individual man to once in 133 000 000 years and for the country as a whole to once in five years. A third protective device, however, involves considerable extra capital expenditure and makes the system so complicated that many people will fail to use it. An alternative is to get every man to inspect his belt and braces every two hours to see if either had broken. This will reduce the failure rate for the individual to once in 36 500 × 8 = 292 000 years and for the country as a whole to 685/8 = 85 men per year This may be considered acceptable, but is it possible to pursuade men to inspect their 'protective systems' with the necessary regularity, and what would it cost in education to persuade them to do so?

This commonplace example illustrates the following general points:

1. The risk can be reduced to any desired level by duplication of protective equipment but it cannot be completely eliminated: some slight risk always remains. Even with three protective devices it could happen that coincident failure occurs not after 133 000 000 years, but next year.

2. The method used above is sound but the result is only as good as the input data. If the failure rate for belt or braces is not once in 10 years but once in 5 or 20 years, then the conclusion will be in error, not by a factor of two, but by a factor of four for two protective devices and by a factor of eight for three protective devices.

3 The event which we wish to prevent is not collapse of our trousers but injury to our self-esteem Half (say) of the collapses will occur when we are alone or at home and will not matter, thus introducing an extra factor of two. In a comparable industrial situation from this point of view, it is not explosions we wish to prevent but the damage and injury they cause; explosions which produce neither are acceptable.

4. A risk which is acceptable to an individual may not be acceptable to the community as a whole.

5. It is easier to devise protective equipment or systems than to persuade people to use them More accidents result from a failure to use equipment properly than from faults in the equipment.

Simpler criteria

Calculation of the FAFR is not essential to hazard analysis, for simpler criteria can often be used. For example, on one chemical plant it was found possible for cold liquid to enter a pipeline and make it brittle so that it might crack.

Instruments were installed to prevent this happening. How reliable should they be? In the event, it was concluded that the probability that the pipeline would leak as the result of cold liquid entering should be small compared with the probability that the pipeline would fail from all other causes Ref. [10]. We have already noted the need to distinguish to some extent between risk to worker and risk to the public. A.N.A. Dicken Ref. [22] and J.G. Sellers Ref. [23] have described a method for identifying all the circumstances which could lead to an emission of chlorine from a plant and the size and probability of a release. The concentration of chlorine at the plant boundary is then estimated and compared with target figures. A 'nuisance' is considered acceptable once a year; a release causing 'some distress' is considered acceptable once in ten years; and a release which could lead to 'personal injury or risk to life' is considered acceptable once in a hundred years. All these expressions are quantified in terms of concentration and duration.

E.H. Siccama, of the *Directoraat-Generaal van de Arbeid,* the Dutch Factory Inspectorate Ref. [24], has discussed the risk to the public from the storage of acrylonitrile. His paper is interesting as an example of the use of a quantitative approach by an official body. He estimates that, if a tank is situated 2500 metres from a residential area, the general public risks suffering 'irreversible negative effects' once in 60 000 years. If there are six tanks in a group, the effects will be suffered once in 10 000 years, which Siccama considers acceptable The figure of once in 10 000 years, is in fact, the frequency with which dykes in Holland are liable to be flooded and results (Table 2) in a risk of death for the people living behind the dykes of 10^{-7} per person per year. The argument, presumably, is that if resources are not being spent to reduce the risk of flooding and drowning below a certain level, why should the risk of acrylonitrile escaping and gassing people be made smaller than this?

Toxic gas releases are also discussed in the Canvey Island Report Ref. [19] where large numbers of casualties are considered possible, though unlikely. The experience of the industry, however, is that when toxic gasses have been released, the number of casualties have been relatively small, about 0.3 per tonne for chlorine and 0.02 per tonne for ammonia Ref. [25].

Hazards of a different kind may arise in the transport of potentially dangerous materials by road. For example, an intermediate product was carried 200 miles by road for further processing. The intermediate was in the form of an aqueous solution and was harmless, but money was being spent simply to transport water. It was, therefore, proposed to transport instead an alternative intermediate which was water-free but corrosive. In this way the total quantity to be transported would be reduced by over 80 per cent. The problem that had to be answered was whether the risk to the public from the transport of a hazardous chemical was so low that it should be accepted, bearing in mind that a safer, though bulkier, material could be transported instead. It was assumed as a matter of course that the transportation would be carried out in vehicles of the highest quality by well-trained drivers.

Using average figures for the number of people killed in ordinary road accidents and in accidents involving chemicals, it was possible to show that reducing the volume of material to be transported by five-sixth would, on average, save one life every 12 years, even allowing for the fact that an accident involving a tanker of corrosive chemicals is slightly more likely to result in a fatality than an accident involving a tanker of harmless material.

The cost per life saved

Earlier in this article I said that I preferred 'target setting' to 'weighing in the balance', but perhaps we should look more closely at the latter, as it may be useful as a secondary criterion. If we adopt the targets I have described, how much will we have to spend to save a life and how does this compare with the money spent elsewhere?

There are many fields in which people have to decide how much money to spend to save lives. The judgements are usually implicit. People do not consciously say, 'We will spend up to £ 100 000 to save a life', but nevertheless, the money allocated and the number of lives saved enable us to calculate what is actually involved. By collecting a number of such figures we should be able to find out the value society actually places on human life.

As Craig Sinclair Ref. [26] has shown, the value placed on a human life in industry varies over a large range. In agriculture, £ 2000 is spent to save an employee's life; in steel handling £ 200 000; and in the pharmaceuticals industry £ 5 million. On the whole, the new industries spend more than the older ones. On the other hand, the pharmaceuticals industry values the lives of third parties at only £ 10 000.

In marked contrast, doctors can safe life for, comparatively, very small sums. Gerald Leach, for example, quotes the following figures at 1972 prices Ref. [27]:

	£
Lung X-rays for old smokers	400
Cervical cancer screening	1 400
Breast cancer screening	3 000
Artificial kidney	9 500
Isotope-power heart	26 000

One medical writer, unaware of the money spent to save life in other fields, has written Ref. [28]:

'The total cost of a bed in an intensive care unit can be as much as £ 450 per week. In other words a ten-bedded unit costs nearly £ 250 000 a year to run, and it has been estimated that of about 500 admissions 50 lives are saved annually at a cost approaching £ 5000 per case. Such astronomical costs naturally raise the question as to whether it is ethical to concentrate so much resource on so small a number of patients when there are many neglected areas of medical care'.

In the chemical industry, experience has shown that to achieve the levels of safety proposed in earlier sections we have to be prepared to spend up to 1 million £ or so per life saved. If a particular proposal calls for the expenditure of more money than this, then it seems that we are not spending our own or the nation's resources wisely. This does not mean that we should accept the risks; instead, we should look for a cheaper solution. Experience shows that, in practice, it can usually be found.

Once we say that risks must be removed if they are cheap to remove, but can be accepted if they are expensive to remove, then every risk may become expensive to remove. If, on the other hand, we can say that all risks above a certain level (which may vary from industry to industry and from time to time) must be reduced, then, in practice, technologists will find a 'reasonably practicable' way of doing so.

Despite the publicity given to the single incident at Flixborough, the figures quoted earlier prompt me to ask if the chemical and process industries are too safe. Do we spend too much of the nation's resources on removing the risks to employees and the public created by this sector? Would the money and time spent save more lives if some of it was used instead to take some of the risk out of coal mining or the construction industry or road transport? *Would I be better employed in persuading people* not to *smoke?*

Unfortunately, if the process industries spent less on safety there is no social mechanism by which the money saved could be allocated to, say, the mines or roads. Also, society does not advance, in any field, by marching uniformly over a broad front. It improves by spear-heading; one firm or industry goes out in front and shows what can be done, and the rest follow. The process industries, and many of the other newer industries, despite the intrinsic hazards of the materials they use, and despite a few incidents that have hit the headlines, have demonstrated that a high standard of industrial safety can be achieved. Perhaps the construction industry and other high-accident industries will now follow this lead. Nevertheless, some levelling out is perhaps desirable. In Britain, the Government controls directly both the nuclear industry and the health service, yet the implicit life valuations in these two industries are vastly different.

The future

The use of hazard analysis in the process industries is now well-established. What changes are likely in the next decade? Hazard analysis has been applied mainly to acute hazards, those that produce their effects immediately. We are likely to see an extension of the methods to chronic hazards, those that take a long time to produce their effects, such as some toxic chemicals, asbestos, radiation, noise. First indications are that, within an order of magnitude, the criteria already established for chronic hazards are in line with those established for acute hazards.

To some people, the approach of this article may seem cold-blooded and callous, I do not think it is. Safety, like everthing else, can be bought, but only at a price. The more we spend on safety, the less we have with which to fight poverty and disease, or to spend on those goods and services which make life worth living, for ourselves and others. Whatever money we make available for safety we should spend in such a way that it produces the maximum benefit to our fellow men. There is nothing humanitarian in spending lavishly to reduce a hazard because it hit the headlines in the past and ignoring the rest.

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